FUNDAMENTAL ASPECTS OF SLUDGE FILTRATION AND EXPRESSION

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SUMMARY

The filtration and expression behaviour of sewage sludge is discussed. Due to the increase of costs for controlled dumping and transport and more severe environmental legislation the need for decreased sludge volumes is rising. Filtration and expression are the cheapest dewatering operations and it is therefore desirable to remove the maximal feasible amount of water by mechanical dewatering. High dry solids contents of 35-40 wt% can already be reached at pressure of 300-400 kPa and optimal flocculation conditions; however at pressures of 6-10 MPa dry solids contents of 60 wt% can be reached. Further the modelling of the dewatering is discussed; model and experiment show acceptable agreement.

1. INTRODUCTION

In the Netherlands sludge production from municipal waste water treatment plants is still increasing; on dry solids base the 1988 production was 282,000 tons and a conservative estimate for the year 2000 is 400,000 tons/yr. As is illustrated in Fig.1, after 1985 the use in agriculture and compost/soil production has been decreasing, and virtually all the rest has been disposed of by controlled dumping. Incineration still only accounts for a few % of sludge disposal. In the future the use in agriculture will decrease due to the increase of more severe limits of allowed heavy metal concentration; an overview is given in Fig.2. Costs of controlled dumping as well as those of transport are rising and environmental regulations tend to decrease the number of available sites. It is therefore to be expected that incineration and possibly other processes, like wet oxidation, will increasingly be needed in the future to dispose of the waste sludge. A decrease of the sludge water content is of the utmost importance in all cases to decrease transport costs. For controlled dumping it is necessary to decrease needed site volume. For incineration it is needed to operate under autothermal combustion conditions to decrease energy costs and decrease capital and operating costs by reduction of the flue gas stream from the incinerator. As stated by van Starkenburg and Rijs [2] in their view of needs for future research: "The processing of sewage sludge to yield a useful product is in fact an option of the past. The main objective of the methods of sludge processing therefore is reduction of the problem by reducing the volume".

![Fig. 1. Production and disposal of sludge in the Netherlands (after data of Werumaus Buning [1])](image-url)
The dry solids content of sludge before dewatering treatment is typically 2-4 wt%, while after mechanical dewatering in practice dry solids contents of 17-25 wt% are typical. In some cases ds-contents of 30 wt% have been found. The targets for dewatering research may thus be presented as in Fig.3. Taking the present average water content after dewatering at 4 kg water/kg ds, we must aim at a reduction in future to 1.5 kg water/kg ds, corresponding to 40 wt% solids. This would mean that in spite of an expected growth of sludge from 300,000 tons dry solids/yr. now to 400,000 tons dry solids/yr. in 2000, we would still have a considerable reduction in tonnage dry solids will also result. Thus very roughly a potential savings of Dfl. 80,000,000/yr. could be seen as a reasonable target.

As stated by the previous cited authors, van Starkenburg and Rijs [2], about dewatering research: "What generally happens during the processing of sludge is still largely unknown. Research in this field should proceed without delay". In the following we will report on progress made in understanding and quantification of the phenomena crucial to the dewatering by means of filtration and expression, following from the study done at our laboratory by the Sludge Dewatering Projectteam: ir. Arend J.M. Herwijn, drs. Erik J. La Heij, and ing. Paul M.H. Janssen, in co-operation with dr.ir. W. Jan Coumans and prof.dr.ir. Piet J.A.M. Kerkhof. Also a considerable contribution has been made by our undergraduate students of which 10 have done their Ir-thesis on this subject; a very valuable contribution was made by ir. Gerben D. Mooiweer in guiding statistical interpretation of results. The project takes up about 15 % of the larger Dutch national project: "Municipal Waste Water Treatment 2000 (RWZI-2000)". Roughly we have divided
the field into two themes: sludge characterization and dewatering fundamentals. On the former dr. Coumans reports during this workshop [3].

At the first workshop in Heelsum we have indicated some of the phenomena we had at that time been studying for somewhat more than a year [4] and indicated some possible directions for modelling filtration and expression. In the following we will treat some of our progress in this area and will discuss the relevance for practical operation.

2. LABORATORY EXPERIMENTS

In order to study the filtration and expression behaviour we have made several laboratory set-ups which we will describe in short in the following paragraphs.

2.1. The Filtration-Expression Cell (FE-cell)

The cell, as shown in Fig.4, consists of a perspex cylinder with a porous bottom-plate. Before filtration a filter paper is placed on the porous plate and the flocculated sludge is introduced into the cell. After that gas pressure is applied to the space above the sludge and filtration starts. The filtrate is collected in a beaker on a balance and data are transferred to an on-line computer. After filtration has been completed a non-porous piston is placed on the sludge cake and gas pressure is applied above the piston. Thus the filter cake is expressed and the expression rate is again followed by means of the liquid flowing to the balance. In some experiments first a gravity filtration is carried out, after which an additional amount of water is added, which is pressed through the fixed sludge amount under pressure.
2.2. The Compression-Permeability Cell (CP-cell)

In modelling the dynamic flow of filtrate during filtration and expression the relations between permeability, porosity, and compressive pressure are of great importance. The CP-cell with which these relations are determined is shown in Fig. 5. It consists again of a perspex cylinder with a porous metal bottom plate, on which a filter paper is placed. Flocculated sludge is introduced and a double piston system is lowered upon the sludge. The lower piston is porous, and the space between the pistons is filled with water. By applying gas pressure on the upper, solid piston, a compressive force is exerted on the sludge mass. Through a tube a small flow of water is allowed to flow through the lower piston, the sludge cake and the filter medium. By registration of the flow rate and of the liquid pressure difference the permeability can be measured. By means of a displacement transducer the cake thickness is known, from which the porosity can be deduced.

2.3. Pressure Distribution Cell

This cell is constructed in the same fashion as the filtration cell, but it has been equipped with a number of capillaries of different length, which are connected to pressure transducers. With these tubes it is possible to measure the liquid pressure at different heights inside the filter cake. By using a mixture of clay and glycerol as a piston a sludge filter cake can be expressed.

3. EXPERIMENTAL RESULTS

3.1. Filtration and expression experiments

Typical experimental results of a filtration experiment are shown in Fig. 7, in which Eindhoven sludge, flocculated with 10 wt% FeCl₃ on dry solids basis was filtered at 0.5 bar pressure difference in the filtration cell at different initial solids contents of the sludge. A first interpretation of such filtration curves is to determine the effective specific cake resistance \( \alpha \), as defined by:
\[ \alpha = \frac{R_c}{w} \]
\[ R_c = \frac{\Delta p}{\mu u_1} = \frac{L_c}{K} \]

in which \( R_c \) is the cake resistance, \( w \) is the cake mass per unit area, \( \Delta p \) is the filtration pressure, \( \mu \) is the liquid viscosity, \( u_1 \) is the superficial liquid velocity, \( L_c \) is the cake thickness and \( K \) is the permeability.

The specific cake resistance is a good measure of sludge characteristics and will depend on the type of sludge, the flocculation treatment and on the filtration pressure. A typical example is shown in Fig. 8, in which \( \alpha \) is plotted vs. the dosage of \( \text{FeCl}_3 \). In this case a minimum is observed, indicating an optimal dosage of flocculant around 100 g/kg dry sludge. With other sludges the increase at overdosage is not as clear as in this picture, but is always of the order of 10 % or higher. Analogous results have been obtained with addition of polyelectrolytes, which is illustrated in Fig. 9.

In Fig. 10 the expression curve of a filter cake is shown. Characteristic is the rapid initial expression, followed by a slow consolidation.
In Fig. 11 results of high pressure expression are shown. It can be seen that dry solids contents of 60 wt% can be reached at pressures of 10 MPa. The values shown in Fig. 11 include flocculant dosage.

3.2. Permeability and porosity in relation to compressive pressure

In Fig. 12 and 13 results of typical compression-permeability experiments are shown. Relations between porosity \( \varepsilon \), permeability \( K \) and compressive pressure \( p_s \) are found. In most cases these relations can be fitted with a power law function (van Veldhuizen [6]). Relations which can be used are (Tiller et al. [7]):

\[
\varepsilon = \varepsilon_0 \left(1 + \frac{p_c}{p_a}\right)^{-\lambda}
\]

\[
K = K_0 \left(1 + \frac{p_c}{p_a}\right)^{-5}
\]

where \( \varepsilon_0 \) and \( K_0 \) are the porosity and the permeability at zero compressive pressure respectively; \( \lambda \) and \( \delta \) are compressibility coefficients and \( p_a \) is an arbitrary constant. Compression-permeability experiments are also very useful for characterisation of different sludges. It quickly gives an idea of the compressibility of the sludges and therefore about the dry solids contents at different applied expression pressures.
3.3 Pressure distributions in sludge filter cakes

In Fig. 14 the hydraulic pressure distribution during the expression phase of an Eindhoven sludge filter cake flocculated with FeCl₃ and Ca(OH)₂ is shown. The first profile in Fig. 14 is more or less (exact transition point is very difficult to determine) the end of the filtration phase, showing hardly any gradient throughout the cake. Only near the filter medium (x/L(t)=0) a steep gradient appears, indicating only compression near the filter medium. This means that the dry solids content after filtration is still very low. At the end of the expression phase the hydraulic pressure throughout the cake almost equals zero, indicating a uniform cake structure.

4. MODELLING THE FILTRATION- AND EXPRESSION BEHAVIOUR.

4.1 Governing equations

To model the filtration- and expression behaviour of sewage sludge attention must be focused on flow through compressible cakes. Therefore flow rate equations, stress balances, constitutive equations and continuity equations are needed. For
the flow rate equation the Darcy-Shirato equation (Shirato et al. [6]) is used which takes into account the solids movement:

\[ v_l - v_s = \frac{1}{\varepsilon} \frac{K}{\mu} \frac{\partial p}{\partial x} \]  

(3)

where \( v_l \) and \( v_s \) are the linear liquid and solids velocity respectively. A simplified force balance leads to the following equation:

\[ \frac{\partial p_l}{\partial x} + \frac{\partial p_s}{\partial x} + (\rho_s \varepsilon + \rho_l (1 - \varepsilon)) g = 0 \]  

(4)

The continuity equation reads:

\[ \left( \frac{\partial \varepsilon}{\partial t} \right)_s = \left( \frac{\partial u_l}{\partial x} \right)_s \]  

(5)

Combination of the above equations leads to a partial differential equation, which describes the change of the porosity in time and place in a filter cake:

\[ \left( \frac{\partial \varepsilon}{\partial t} \right)_s = u_m \left( \frac{\partial \varepsilon}{\partial x} \right)_s + \frac{\partial}{\partial x} \left[ \frac{K}{\eta} (1 - \varepsilon) \left( \rho_s - \rho_l (1 - \varepsilon) \right) g + \left( \frac{\partial p_l}{\partial x} \right)_s \right] \]  

(6)

where \( u_m \) is the superficial liquid velocity through the filter medium, \( \rho_s \) the density of the solids, \( \rho_l \) the density of the liquid and \( g \) the gravity acceleration. Depending on the boundary conditions the filtration- or the expression phase can be modelled (La Heij et al. [8]). However, before the partial differential equation with the right boundary conditions can be solved, a constitutive equation must be chosen.

4.2 Constitutive equations

Constitutive equations describe the deformation behaviour of the solids in a filter cake and can only be determined experimentally. The CP-cell (discussed in section 2.2 and 3.2) is an apparatus to determine these constitutive equations; relations between permeability \( K \), porosity \( \varepsilon \) and compressive pressure \( p_s \). Using the relations found with the CP-cell for modelling, the material is assumed to behave non-linear elastic. This means that at a given compressive pressure the filter cake deforms instantaneously apart from the hydrodynamic resistance. This non-linear elastic material behaviour can be regarded as a spring with a variable elastic modulus \( E_1 \), see Fig. 15. The elastic modulus increases with decreasing porosity.

If it takes some time before the material deforms when a certain compressive pressure is placed on the solids, the material behaves visco-elastic. Different spring-dash pot models can be used to describe the material behaviour. In Fig. 15 a three parameter model is shown. The differential equation describing the strain \( \varepsilon \) as a function of time can be written as:

\[ \left( \frac{\partial \varepsilon}{\partial t} \right)_s = - \frac{\rho_s + E_1 \varepsilon + \tau \frac{\partial E_1}{\partial \varepsilon}}{\left( \tau (E_1 + E_2) + \varepsilon \frac{\partial E_1}{\partial \varepsilon} \right)} \]  

(7)
where \( \tau (=E_2/\eta) \) is the relaxation time. The strain \( \varepsilon \) is related to the porosity \( \varepsilon \) as follows:

\[
\varepsilon = \frac{(1 - \varepsilon_0)}{(1 - \epsilon)} - 1
\]

(8)

The relaxation time \( \tau \) determines the rate of deformation of the material. In equilibrium situation all the pressure rests on spring \( E_1 \) and therefore the same value for pure elastic material for \( E_1 \) can be used. Because the material deformation and the liquid flow through the cake occur simultaneously, the relaxation time \( \tau \) can only be determined directly from a filtration- or expression experiment. Equations (6) and (7) must be solved simultaneously to calculate locally and at every time the change of the porosity in the filter cake.

4.3 Modelling results

Because the porosity can be calculated as a function of time and place, the compressive pressure and therefore also the hydraulic pressure can be calculated. In Fig. 16 calculated hydraulic pressure profiles for the expression phase based on non-linear elastic material behaviour are shown. Compared to the measured profiles, shown in Fig. 14, there is a good agreement between model and experiment. In Fig. 17a the average dry solids content versus the time for different expression pressures are shown, in Fig. 17b the model calculations are shown. The sludge was flocculated at optimal conditions. Again there is an acceptable agreement between experiment and model. According to the model calculations the equilibrium situation is reached somewhat faster than in the experiment. This is caused by the fact that for the model calculations elastic material behaviour is assumed. Further it can be seen from Fig. 17a and b that the final equilibrium situation is reached at the same time regardless of the applied expression pressure. Finally it can be seen from Fig. 17b that already at 400 kPa dry solids contents of about 38 wt% can be reached. In Fig. 18a and b
experiments and model calculations for the expression of sludge flocculated with polyelectrolyte are shown. Because the material deforms quite slowly, visco-elastic material behaviour must be assumed. From Fig. 18b it can be seen that there is a good agreement between model and experiment. In Fig. 19 the expression time versus cake thickness according to experiment and model is shown. Again there is an acceptable agreement between model and experiment. The dewatering time increases with the square of the cake thickness.

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**Fig. 16.** Calculated hydraulic pressure profiles for the expression phase for sludge from Eindhoven flocculated with 10 wt% FeCl₃ and 26 wt% Ca(OH)₂ on dry solids base. Expression pressure 48 kPa

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**Fig. 17a.** Average dry solids content versus expression time, experiment. Miclo sludge flocculated with 15 wt% FeCl₃ and 20 wt% Ca(OH)₂ on dry solids base
Fig. 17b. Average dry solids content versus expression time; model. Miehlo sludge flocculated with 15 wt% FeCl₃ and 20 wt% Ca(OH)₂ on dry solids base.

Fig. 18a. Average dry solids content versus expression time; experiment and model (elastic and visco-elastic behaviour). Miehlo sludge flocculated with 1.5 wt% polyelectrolyte.

Fig. 18b. Average dry solids content versus expression time; experiment and model (elastic and visco-elastic behaviour). Miehlo sludge flocculated with 1.5 wt% polyelectrolyte.
5. CONCLUSIONS

With the above discussed models the dewatering behaviour of sewage sludges can be predicted well. The material behaviour can be either non-linear elastic or non-linear visco-elastic. These fundamental models can be considered to form a good base for actual equipment and operating models, with which optimization of design and operation can be carried out.

Quickest dewatering always occurs at an optimum flocculant dosage (inorganic as well as organic flocculant). Characteristic for the expression of sewage sludges is the rapid initial expression followed by a slow consolidation. The time at which the equilibrium situation is reached, is independent of the filtration/expression pressure. At these equilibrium situations already at low pressures (300-400 kPa) high dry solids contents (35-40 wt%) can be reached. However at pressure of 6-10 MPa dry solids contents of 60 wt% can be reached. Further the dewatering times increase with the square of the cake thickness.

Fig. 19. Expression time versus cake thickness according to experiment and model. Mierlo sludge flocculated with 1.5 wt% polyelectrolyte.
**List of symbols**

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<th>Symbol</th>
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<tr>
<td>ε</td>
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<tr>
<td>$E_1$</td>
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<td>g</td>
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<td>K</td>
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<td>permeability at top of filter cake ($p_s=0$)</td>
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<td>$L_C$</td>
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<td>p</td>
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<td>$v_l$</td>
<td>linear liquid velocity</td>
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<tr>
<td>$v_S$</td>
<td>linear solids velocity</td>
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<tr>
<td>w</td>
<td>cake mass per unit area</td>
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<tr>
<td>$u_{lm}$</td>
<td>superficial liquid velocity through filter medium</td>
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<tr>
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**Greek symbols**

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<td>$\tau$</td>
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**Literature cited**

[1] Werumeus Buning W.G.  
*New techniques of sludge management in the Netherlands*  

*Needs for research in the future*  

*Characterisation of sewage sludges, fundamentals and results*  
Workshop sewage sludge the Netherlands-Japan, 17-23 October, 1993, Miyazaki, Japan.

*Some fundamental aspects of sludge dewatering*

*Compression behaviour of sewage sludge*

*Internal flow mechanism in filter cakes*
AIChE, J., vol.15, no.3, p.405-409, 1969

[7] Tiller, F.M., Yeh, C.S.
*The role of porosity in filtration. Part XI: filtration followed by expression*

*Filtration and expression behaviour of sewage sludge*
presented at the AIChE annual meeting November 1992, Miami Beach.